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ABSTRACT

This document presents a model for a simple transmission electron microscope for educational purposes. This microscope could demonstrate thermonic emission, particle acceleration, electron deflection, and flourescence. It is designed to be used in high school science courses, particularly physics, taking into account the size, weight, complexity and costs. It could also be built by any high school and would enable students to investigate electron optics. The report includes six chapters that cover the purpose, theory, design, construction and operation of the transmission electron microscope model. It also includes some diagrams and a component list. This project was funded by the Educational Research Institute of British Columbia (ERIBC) of Canada. (HM)

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ERIBC REPORTS

REPORT NO.: 78:11

THE DESIGN AND CONSTRUCTION OF A SIMPLE TRANSMISSION ELECTRON MICROSCOPE FOR EDUCATIONAL PURPOSES

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Educational Research Institute of British Columbia

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TITLE: THE DESIGN AND CONSTRUCTION OF A SIMPLE TRANSMISSION ELECTRON MICROSCOPE FOR EDUCATIONAL PURPOSES

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THE DESIGN AND CONSTRUCTION OF A SIMPLE TRANSMISSION ELECTRON MICROSCOPE FOR EDUCATIONAL PURPOSES.

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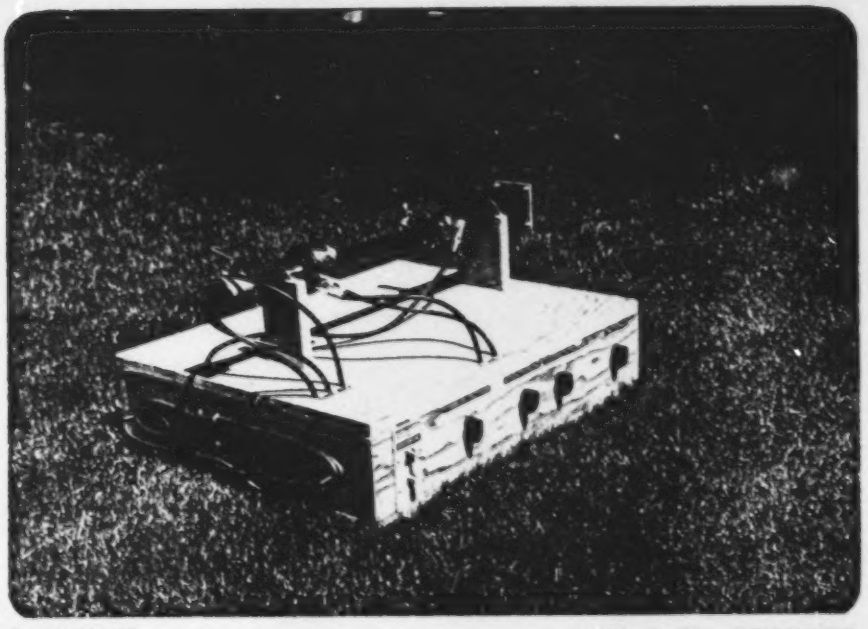

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PURPOSE

A microscope is an instrument used to obtain an enlarged image of a specimen. It can be a transmission optical, a stereoscopic optical, a transmission electron, or a scanning electron type. There are many variations of these four basic types, however; each is suited for a specific investigation.

Optical microscopes, or course, are common and widely used. The magnifying glass is a simple transmission optical microscope. More complex compound transmission optical and stereoscopic optical microscopes are found in schools, universities, hospitals, and laboratories. As the majority of optical microscopes are relatively inexpensive, they are useful for education and research.

Unfortunately, electron microscopes are another story. They are typically large, heavy, intricate, and very expensive. Although they are, in many respects, similar to optical microscopes, they use an electron beam instead of a light beam. The shorter wavelength means a higher resolution and a higher magnification. This makes them highly desirable for research purposes, and many universities, hospitals, and laboratories now boast complete electron microscopy departments.

High schools can, and do, buy optical microscopes for their science microscopes and today many courses are designed with the use of the microscope in mind. Although an electron microscope would be welcome at any school, however, few could afford the ten thousand dollar plus price tag.

Supposing that a high school was somehow able to obtain an electron microscope, one would find that the physics classes benefitted most. Biology and chemistry classes would find little use for one simply because high schools do no research. But most grade twelve physics courses cover particle acceleration and cathode ray tube operation in the electronics sections. A commercial electron microscope would be useful in demonstrating the principles of particle acceleration, but impractical from the standpoint of cost and complexity. The ideal machine would be:

(a) inexpensive,
(b) reliable,
(c) simple,
(d) portable,
(e) hazard free,
(f) easy to repair,
(g) easy to operate,
and (h) open for observation while in operation.

No commercially available electron microscope has these qualifications. Therefore, the purpose of this project was to design and construct an electron microscope with all of the above qualifications. Such a microscope could be built by, and used by, any high school and would enable students to investigate electron optics for the first time.

Incidently, I had to make a choice between the transmission and scanning types at the beginning of the project.

Because a scanning electron microscope (S.E.M.) requires complex circuitry, I chose to build the transmission electron microscope (T.E.M.), and all further discussion of electron microscopes refers to the T.E.M.

THEORY

The TEM is a specialized electron tube, similar to television kinescopes. It consists of three major components contained in an airtight vacuum chamber, with four external systems. These three components are the electron gun, which emits the electrons and forms the illuminating beam; the electromagnetic lens or lenses, which focus the beam; and the viewing screen, which transforms the invisible pattern of electrons into a visible image.

The four external systems are as follows; the evacuation system, which removes the majority of the gas molecules from the vacuum chamber; the emission system, which operates the electron emitting part of the electron gun; the acceleration system, which boosts the electrons to a high velocity; and the deflection system, which alters the paths of the individual electrons and in this way focuses the beam.

The electron gun is actually a type of vacuum triode. Its three electrodes are a cathode, a bias shield, and an anode. The cathode provides the electrons needed for image production, and is usually in the form of a vee shaped tungsten filament. But at ordinary room temperature the free electrons in the filament metal cannot leave its surface because of certain restraining forces that act as a barrier. To escape from the surface the electrons must have sufficient energy imparted to them from an external source, since their own kinetic energy is inadequate. The emission system, typically a low voltage high amperage alternating current power supply,

does this by electrically heating the filament to incandescence. The electrons acquire enough energy through this heating to overcome the restraining forces and they are emitted from the surface of the filament. The number emitted increases exponentially when the filament temperature increases. For this reason, doubling the temperature of the emitter may increase electron emission by more than ten million times. Since the filament life can be greatly reduced by excessive temperature, a compromise is made between maximum life and maximum emission. Most electron microscopes utilize a cathode operated at about twenty seven hundred degrees Kelvin.

An electron microscope depends upon a high velocity electron beam for a number of reasons. Firstly, high velocity electrons have a shorter wavelength than low velocity electrons, and are therefore capable of producing higher resolution images. Secondly, high velocity electrons can penetrate thicker specimens. This simplifies specimen preparation. Lastly, high velocity electrons produce a brighter image when they impact on the screen. So it can be seen that the emitted electrons must be somehow accelerated in one direction. The filament alone can only emit the electrons, which gather in a cloud about it. The anode is the electrode which causes particle acceleration. It is a metal disc having a single aperture in the center. The positive terminal of the acceleration system (a high voltage low amperage direct current power supply) connects to both the anode and ground, and the negative terminal connects to the filament. (The filament, in fact, is not only the emitter in the emission system, but the cathode in the acceleration system). Lines of force now extend from the cathode to

the anode. When the filament is heated, it emits electrons, which, being negatively charged, follow the direction of the lines of force to the anode. From the time they leave the cathode to the time they reach the anode, the electrons are under constant acceleration.

However, the electrons do not stop at the anode. There is an electrical connection between the metal vacuum chamber and the anode, so that all parts of the microscope but the cathode section of the gun are grounded. Electrons which stray from the beam hit the anode, but the majority pass through the aperture to enter field free space. From here they penetrate the specimen, pass the lenses, and hit the screen at the end. Every electron eventually returns through the acceleration circuit. Since moving charges comprise an electric current, the stream of electrons from cathode to anode is called the beam current.

The total number of electrons emitted by the cathode is constant at a given temperature. The anode voltage has no effect, therefore, on the number of electrons emitted. Whether or not these electrons actually reach the anode, however, is determined by the anode voltage, as well as by a phenomenon known as space charge. The term space charge is applied to the cloud of electrons that is formed in the inter electrode space. Since it is made up of negatively charged particles, this cloud constitutes a negative charge in the inter electrode space that has a repelling effect on the electrons being emitted. The effect of this negative space charge, alone, is to force a large number of electrons back into the filament and prevent others from reaching the anode.

The space charge, however, does not act alone. It is counteracted by the electric field from the anode, which reaches through the space charge to attract electrons and partially overcome its effects. At low anode voltage only the electrons nearest to the anode are attracted to it; these constitute a small beam current. The space charge then has a powerful effect on limiting the number of electrons reaching the anode. As the anode voltage is increased, a greater number of electrons is attracted to the anode through the negative space charge and correspondingly fewer are repelled back to the cathode. If the anode voltage is made sufficiently high, a point is eventually reached where all emitted electrons are attracted to the anode and the effect of the space charge is completely overcome. Further increases in the anode voltage cannot increase the beam current and the emission from the cathode limits the maximum current.

So it can be seen that at low anode voltages, the beam current is completely controlled by the anode voltage and is independant of the cathode temperature. Under these conditions the beam current is said to be space charge limited.

At higher anode voltages, the entire supply of electrons is attracted to the anode. The space charge effect is completely overcome and the beam current becomes independant of the anode voltage, reaching a constant value equal to the total emission. Emission saturation takes place and the beam current is said to be emission limited.

The bias shield is the third electrode which completes the gun. It is tubular, with an apertured disc at one end. The cup like shape surrounds the cathode, with the apex of the fil-

ament centered just behind the aperture.

Since the bias shield is nearer to the cathode than the anode, a potential placed on the shield has a much larger effect on the electric field within the gun- and hence upon the beam current - than the same potential placed on the anode. The shield thus has a controlling effect on the flow of electrons. A bias shield in what would otherwise be a diode gun acts as a valve which can restrict or even halt the electrons, depending on its applied potential. This potential is the shield bias and is usually up to five hundred volts negative with respect to the cathode.

In operation, the cathode emits a large number of electrons; the anode is at a high positive potential and would normally attract a large number from the space charge if it were not for the shield bias. Because of this negative potential, the electrostatic field existing between cathode and anode is partially offset and less electrons are able to reach the anode. A large space charge accumulates in the region between cathode and shield. The bias that is just capable of cutting off all electron flow is called the cutoff bias. Bias voltages higher than this can have no further effect.

Electrons emitted from the cathode tend to diverge because they repel each other. However, electrons are forced to converge to a narrow beam by the electrostatic field between cathode and shield. So the bias shield has a number of functions: it can allow all, some, or none of the electrons to reach the anode; it retards stray electrons which otherwise cause a blurring effect on the screen image; and it focuses the beam somewhat by causing the electrons to converge. (In fact, the bias vol-

tage can be adjusted to cause the beam to cross itself. The crossover point is smaller than the area of the filament tip emitting the electrons and it is this crossover which is used as a point source).

The lenses of an electron microscope are electromagnetic. Each lens consists of a coil of copper wire contained in a soft iron cylinder. The magnetic field around a wire carrying an electric current takes the form of concentric circular lines of force, diminishing in intensity as the distance from the wire increases. The direction of the circular lines of force reverses if the current is reversed. A permanent magnet placed near a current carrying wire becomes aligned with the direction of the lines of force; it is neither attracted to nor repelled from the wire. If, however, a current is passed through a loop of wire, the resulting field of force resembles that of an ordinary bar magnet, with the perpendicular axis of the loop as the North South axis of the magnetic field. When a number of loops are formed from the wire by winding a helical coil, the magnetic effect is greatly strengthened, because the fields of the individual loops reinforce each other. A coil of this type is known as a solenoid. If a piece of iron or other ferromagnetic material is placed within a solenoid, the intensity of the magnetic field inside the iron is far greater than the intensity caused by the same amount of current flowing through the solenoid alone. The number of lines of force crossing each square centimeter of the solenoid interior is known as the flux density. This quantity is increased hundreds of times by the introduction of a core. The amount of increase depends on the material of which the core is made. The ratio

between the flux density of a solenoid with a core and the same solenoid without a core is known as the permeability of the core material.

A definite amount of force is necessary to produce a magnetic flux. This force, known as magnetomotive force, is directly analogous to the electromotive force (voltage) in an electrical circuit, and is measured in terms of gilberts, which are defined as the amount of work necessary to move a unit pole around the magnetic circuit. Magnetic circuits also exhibit varying amounts of resistance to the passage of magnetic flux. This resistance is inversely proportional to the permeability of the core material and is called reluctance. It is analogous to resistance in electrical circuits. The relation between flux, magnetomotive force, and reluctance is also analogous to the Ohm's Law relation of voltage, current, and resistance; the flux is equal to the magnetomotive force divided by the reluctance.

When the current in a solenoid with an iron core is increased steadily, the flux density increases slowly at first, and then quickly, and finally reaches a point where a large increase in the magnetizing force produces comparitively little more flux. During the same period the permeability of the iron rises sharply and then declines. For this reason magnetizing iron beyond a certain flux density is impractical. (This condition of maximum flux density is known as saturation).

When a piece of iron is magnetized by an increasing current and then demagnetized by reversing the current, the magnetic flux lags behind the current and the iron remains slightly magnetized when the current drops to zero. To remove this residual magnetism, additional energy must be expended. This property of iron and other ferromagnetic materials is known as hysteresis and is an important factor in the design of electromagnetic lenses.

So an electron microscope lens consists of a solenoid placed in a soft iron shroud. The shroud reinforces the magnetic field and forms a magnetic circuit whenever current from the deflection system (typically a medium voltage, high amperage direct current power supply) is applied to the solenoid within. This magnetic circuit is complete except for where there is a gap in the polepiece. In order to complete the circuit the lines of force cross this gap, and it is this part of the field that affects the trajectories of the individual electrons of the beam.

The magnetic field is a strong localized axial field in the direction of the electron beam. The envelope of the beam is analogous to that of a light beam passing through a converging lens, except that the electrons travel in a helical path as they pass through a magnetic lens. Since the rotary motion does not affect the focussing behavior of the lens, the ray diagrams for a beam through an electromagnetic lens are identical with those for a light beam through a glass lens, and the lens formulae for light optics apply.

In a magnetic electron lens the focal length is determined by the field strength in the lens gap and by the velocity of the electrons (which is determined by the acceleration voltage of the electron gun). The field strength of the lens can be varied by altering the output of the deflection system. This creates a variable lens, something impossible for an optical microscope. Also, for a beam of more energetic electrons, the lens current must be increased in order to keep the focal length constant.

Most commercial T.E.M.s have two to five electromagnetic lenses: one or two condenser lenses, which focus the electron beam onto the specimen; an objective lens, which forms an intermediate image; and one or two projection lenses, which further magnify and project the image onto the viewing screen. The specimen, mounted on a copper grid, is carried in a small holder within the objective lens (which has a short focal length of one to five millimeters). Each electron in the beam experiences a force in the magnetic field of the condenser lens. The direction of the force is perpendicular both to the direction of motion of each electron and to the magnetic field, so that the particle is deflected from its original path. An electron travelling through the exact center of the lens will not be deflected and will continue on its way past the lens. An electron not travelling through the exact center of the lens is deflected towards the center axis. When a beam of electrons passes through the lens, it is focussed in this way into a narrow beam. This beam is focussed by the condenser lens onto the specimen, and the electrons, in passing

through, are scattered according to the specimen's composition. The scattered beam is magnified by the objective lens and the beam leaving this lens is further magnified by the projection lens. The beam now falls on the viewing screen, where the scattered electrons form a pattern or image.

However, as the electrons cannot be seen hitting the screen, no visible image is apparent. So the viewing screen is coated with a thin, uniform layer of phosphor. This phosphor is composed of minute crystals of zinc sulfide activated chemically by traces of cadmium. The zinc sulfide crystals transform the kinetic energy of the electrons into light energy by fluorescence. High speed electrons striking the crystals cause electrons within the atom of the crystal lattice to move up to higher energy levels. As these electrons fall back to their original energy levels, energy is radiated in the form of visible light. Each crystal represents a unit from which light is emitted. The resolution of the screen image is therefore determined by the size of these crystals. Usually the crystal size is not sufficiently small to allow all the details of the image to show up on the screen.

The recording of the image on photographic plates or film is possible because the electrons hitting the photographic emulsion will produce changes in the silver bromide crystals similar to those produced by light.

So a complete T.E.M. consists of an electron gun mounted at one end of a chamber, with several electromagnetic lenses spaced along the length of the chamber and a phosphor viewing screen mounted at the far end. But high voltage electrons can

penetrate only a few centimeters of air before being stopped through repeated collisions with air molecules. These collisions result in a scattering of the electrons, which would ruin the possibilities of obtaining well defined pictures in the microscope. Therefore, it is obvious that the electron beam must pass through a well evacuated space.

The high voltage difference between cathode and anode would cause discharges if there were a sufficient number of gas molecules present to allow ionization to take place in this space. This factor makes it necessary to keep a particularly low gas pressure at the electron gun. Discharges in the gun are an indication of insufficient vacuum, which in turn can be caused either by a leak or by evaporation of gas from internal surfaces (outgassing).

A good vacuum furthermore increases the lifetime of the filament by preventing too fast oxidation of the tungsten and deterioration through bombardment by positive ions.

Insufficient vacuum thus will be recognized by discharges, by short life of the cathode filament, and by rapid contamination of the electron gun region.

The air pressure used in modern T.E.M.s is usually 10^{-4} to 10^{-5} millimeters of mercury, which is in the range of "high vacuum". As a comparison, the atmospheric pressure is 7.6×10^{2} millimeters of mercury. Now, the pressure exerted by a column of mercury one millimeter in height at zero degrees Celsius is called "one torr". A pressure of 10^{-4} to 10^{-5} torr is approximately one ten millionth to one hundred millionth of atmospheric pressure. For this reason a very efficient evacuation system is needed.

It is useful to know some basic gas kinetics in order to understand the parts of a vacuum system. In a gas, the gas molecules move in a random fashion, repeatedly colliding with each other. The average distance a gas molecule moves between collisions is called its mean free path. This distance increases with decreasing gas pressure, since the average distance between the gas molecules increases.

In a stream of gas with layers of gas molecules moving at different velocities, the faster moving molecules will move into the layers of slower moving molecules, whose velocities will then be increased by the resulting collisions. On the other hand, molecules in the slower moving layers will move into the layer of faster moving molecules and through collisions with the latter will exert a retarding effect on the stream. There is a tendency, therefore, toward elimination of the difference in velocity of the streaming in adjacent gas layers. This means a certain inertia which must be overcome to increase the velocity of streaming. The streaming gas exerts a certain viscosity. These features of streaming gas are of importance in a consideration of gas molecule movement at pressures above 10^{-3} torr.

At pressures below 10^{-3} torr, the mean free path of the gas molecules becomes useful for electron microscopy. The mean free path at atmospheric pressure is 6.5×10^{-8} meters; at 10^{-4} torr it is 2.5 meters; at 10^{-6} torr it is 49.4 meters; and at 10^{-8} torr it is 5 Kilometers.

When comparing the mean free path of the gas molecules and the dimensions of the microscope's vacuum chamber and of the vacuum connections, it is found that the inner diameters of these parts are small in comparison with the mean free

path of the molecules at the high vacuum maintained in the microscope. The probability for a collision of the gas molecules with the walls of the chamber therefore becomes greater than a collision between gas molecules.

The collisions between gas molecules are elastic collisions; that is, they are not interfered with by attractive or repellent forces. The collision with the walls of the vacuum chamber, on the other hand, can be considered comparable to a condensation and an evaporation with a random direction of the movement of the evaporated molecules. If the gas molecules hit a moving surface, on the other hand, they will be accelerated in a direction parallel to the direction of the movement of that surface. These factors are of importance in the dimensioning of a high vacuum chamber for an electron microscope.

The evacuation system uses pumps of two types, operating on different principles. They differ with respect to the pressure at which they exert a pumping action, the end vacuum that can be reached, and the speed at which gas is removed.

Some types of pumps can work at atmospheric pressure; other types are efficient only at a reduced gas pressure since their action is dependant upon a certain minimum mean free path of the gas molecules which must be longer than that of air molecules at atmospheric pressure. In the latter category are the pumps that can develop and maintain a high vacuum. The type of pumps in the former category is used in order to reduce the initial gas pressure sufficiently to allow the high vacuum pump to work. They are called backing pumps when used for this purpose.

Most backing pumps are mechanical rotary pump . In these pumps, an eccentric rotating cylinder produces a continuous streaming and compression of the gas, the compression being confined to the outlet side of the pump through valving mechanisms. The end vacu m of this type of pump cannot exceed the vapour pressure of the oil contained within the pump. Contamination of the oil with a component of higher vapour pressure than that of the oil-for instance, water -will change the end vacuum toward higher pressure.

The other type of pumps, which are efficient only at reduced pressures, are known as mercury diffusion pumps and oil diffusion pumps. These pumps operate on the principle that the diffusion of gasses is independant of the total gas pressure and depends on the partial pressure of the gas. Therefore, a gas will diffuse into a space of higher total pressure as long as the partial pressure of that gas is kept low in that space.

The air molecules diffuse into a stream of mercury or oil vapour which is maintained through continuous heating and cooling of mercury or oil.

These pumps demand a backing vacuum to increase the mean free path of the gas molecules to more than one millimeter and also to remove the air molecules from the mercury or oil in connection with the condensation of the vapour. The backing pressure is usually about 10^{-1} torr.

The end vacuum depends on the vapour pressure of the mercury or oil: good oil diffusion pumps can attain 10^{-6} to 10^{-7} torr, while mercury diffusion pumps require liquid nitrogen cooled cold traps to attain the same performance. Since

the vapour pressure of mercury is about 10^{-3} torr, the cold trap condenses any vapour that would otherwise reach the vacuum chamber. The pumping speed of diffusion pumps depends on the dimensions of the pumps, and in electron microscopes pumps with a pumping speed of several hundred litres per second are used.

The oil of oil diffusion pumps can become oxidized if exposed, while hot, to high air pressure. The oxides so formed have a higher vapour pressure and increase the end pressure that can be reached. Air pressure, therefore, is never allowed to exceed one torr in the system while the oil is hot.

The operating procedure for a T.E.M. is a complex, step by step one. Briefly, this involves inserting the specimen and activating the backing pump. Once pressure is about 10^{-1} torr, the diffusion pump is activated. At a pressure of no more than 10^{-4} torr, the acceleration system can be turned on. The emission system is switched on, and when the filament temperature is adjusted for optimum performance, the bias on the bias shield is set to provide a crossover of the beam. Finally the deflection system can be activated and the individual lenses adjusted until a focussed image appears on the viewing screen.

DESIGN

When I first sat down to design a transmission electron microscope, it occurred to me that the best approach would be to follow a proven design and then modify it to meet my requirements. In an old issue of Scientific American I found a simple microscope, engineered by a group in Chicago. It appeared to be perfectly straight forward and therefore construction began in November of 1976. Three electromagnetic lenses were mounted in an aluminum vacuum chamber, with a specimen airlock passing through the objective lens. When I finished the microscope in March of 1977, a power supply was connected to each lens, the filament of the gun, and the acceleration section of the gun. A high vacuum mechanical pump was set up to evacuate the chamber. Although the microscope seemed to be in working order, I never once had it operate properly. Through experiments and further research, it became evident that there were several faults in this design. First of all, the vacuum chamber was impossible to seal. So many minute leaks existed that a proper vacuum could not be reached. Secondly, no material could be found to insulate the cathode section of the gun from the anode. Discharges constantly occurred when the acceleration voltage was applied. Thirdly, the specimen airlock was another area where sealing problems persisted. Also, since one lens can adequately demonstrate electron deflection, I felt that the work involved in building three lenses had not been justified.

In April of 1977 I built Model 2, using a number of parts

salvaged from Model 1. It had a vacuum chamber made of glass and plastic, and a single lens was mounted on this. Also, the electron gun was a concave, cold cathode type. This gun was to simplify the electrical system by eliminating the emision circuitry. Model 2 solved the problem of a discharging gun but still had a leak problem. Because the vacuum chamber consisted of four sections, there were many leaks too minute to locate. Other problems with my second model included: an undersized exhaust port which resulted in decreased pumping efficiency; a viewing screen with an excessively thick layer of phosphor; and a section of vacuum chamber which could not tolerate the heat from the gun cathode. By this time I felt I had learned enough to create a new design. This microscope would be the simplest yet and would minimize or eliminate the problems I had encountered in my previous models.

In May of 1977 I started my Model 3. I designed a heavy walled one piece glass vacuum chamber which had a large exhaust port, and could easily tolerate the heat from the electron gun. The fact that this chamber was a single unit meant, of course, that there was less chance for a leakage problem to occur. Since glassworking is a complex art, I was extremely fortunate to have my chamber made for me at the University of Victoria. A flange at each end increased the area of the seals so that I could now use O rings.

The electron gun was of the filament cathode type. The body of the gun, machined from a block of solid brass, served as the bias shield connection. Insulators made from glass tubing surrounded the two filament leads. A groove machined

in the gun body accomodated a single O ring, so that atmospheric pressure would tighten the seal during chamber evacuation. Miniature wire clamps served as filament holders, and the shield, with a two millimeter aperture, was made from a brass tube.

Since bringing the anode lead out at the gun would cause insulation problems, I fastened the anode four centimeters down from the shield. In this way the glass of the chamber itself would serve as the gun insulator. A conducting paint known as "aquadag" was applied to the inner surface of the chamber, from the anode to the viewing screen. Near the exhaust port, a special tungsten wire was sealed through the glass and this connected to the aquadag coating. Thus the cathode and anode leads were well separated, and the coating, in extending the anode, would also allow the electrons to pass through field free space.

The specimen grid holder was similar to the bias shield but had a perforated disc which clamped a specimen grid over the aperture. It fit snugly within the tubular brass anode and was actually a working part of the anode.

The single electromagnetic lens was machined from six millimeter iron plate and pipe. The energizing coil was twenty two gauge copper wire, and the lens gap was set at five millimeters. The center of the lens was placed ten millimeters from the specimen plane.

The viewing screen was a six millimeter glass plate fastened to the chamber flange by spring clips. The phosphor powder was spray painted onto a circle of celluloid, which

was attached to the inner surface of the screen with small dabs of contact cement. There was no way to cut an O ring groove in the glass screen, so I relied on a thin film of high vacuum grease between screen and flange to form the seal. This, I found, was a very efficient method.

The evacuation system consisted of an air cooled oil diffusion pump backed by a mechanical oil pump. I recommend the Sargent-Welch Model 1392 mechanical diffusion combination, which pumps ten litres per second at 10^{-4} torr and can attain 10^{-6} torr. A short length of high vacuum tubing (twelve millimeter I.D.) was fastened to the exhaust port of the vacuum chamber and the intake port of the diffusion pump.

The emission, acceleration, and deflection systems were built as one complete electrical system, and were mounted in a heavy plywood box. This was necessary to prevent electrical shock; the high voltage can be lethal. The emission system consisted of a hand-made transformer and a variable resistor. The acceleration system was made up of a variable transformer, a luminous tube transformer, two diodes, a capacitor, and a variable resistor. The deflection system was a transformer, a bridge rectifier, two capacitors, a resistor, and a variable resistor. All high voltage wiring used seven millimeter silicone insulated steel sparkplug wire.

Model 3 turned out to be the most sucessful T.E.M. I had built: it met every one of my requirements. One or two people can build my Model 3 in a few months of spare-time work. I would estimate the total parts cost of the microscope (including vacuum pumps and electrical components) to be close to $1500,

and of this $1000 is for the vacuum system.

CONSTRUCTION

Here is a rough guide to the construction of my TRANSMISSION ELECTRON MICROSCOPE MODEL 3. The order in which components are made is not particularly critical, but it is safest to follow instructions as closely as possible.

VACUUM CHAMBER-

The chamber cannot be made by an amateur. As I mentioned earlier, glassworking is a complex art and is best left to the professionals. Anyone thinking of building the Model 3 should make certain that the chamber can be locally made by either a university shop or a commercial firm. Once a tungsten anode lead is sealed into the Pyrex glass, the chamber must be annealed to relieve the internal stresses. Also, have the glassworker apply some silver paint to the area around the anode lead. This will ensure a positive connection between the lead and the aquadag coating.

ELECTRON GUN-

The gun body is turned on a metal lathe, while the insulator holes can be bored on a drill press. Always take your time and machine cautiously - it is very easy to cut too much and ruin a component. To make each filament lead, insert the steel wire in the glass tube and rotate one end in the flame of a propane torch until the glass melts around the wire. Slip the filament holder over the wire and solder. Line up the two completed filament leads in the gun body and fill the cavity with epoxy glue, which must set well. Instead of buying tungsten wire for filaments, I used the filaments from old radio

tubes. A fifteen millimeter length is bent into a sharp V over the edge of a razor blade (bend it slowly, as the tungsten is usually brittle) and clamped securely in the filament holders. To make the bias shield, solder a disc of brass on the end of the shield tube, using silver solder, and file down the excess solder and brass. Drill a two millimeter aperture at the exact center and remove any burrs that may obstruct the hole. Once the completed shield is inserted in the shield recess of the gun body, the filament can be centered behind the aperture, and the O ring can be lightly greased and set in its groove (the groove should be wide enough to allow for the expansion of the O ring which occurs when the vacuum pulls the gun in tightly).

The anode is just a length of brass tube, wound with copper wire to increase its diameter. It should fit snugly within the vacuum chamber, so that vibration will not cause it to shift. Once set in position, aquadag is painted on the inner surface of the chamber. It should contact the anode, and stop just short of the screen flange.

The specimen grid holder is a length of brass tubing made in the same was as the shield. It has a stop, made from a piece of larger tube, with two holes allowing manipulation by a simple hook of wire. A perforated brass disc which bolts to the end plate of the holder retains the grid. The grid itself cannot be made, as it is only three millimeters in diameter and has many lines per centimeter. I'm sure a local university would have a few spares. Any electron microscopy supplier should also have them in stock.

LENS-

The lens is very easy to make; it has all parts machined from iron plate and pipe. Press fits eliminate the need for screws. The coil can be wound on a cardboard form, taped to prevent unwinding, and slipped into the lens housing.

VIEWING SCREEN-

The screen can be cut from a thick plate of glass. A piece of three millimeter plywood is cut to the size of the screen, and a hole cut the same size as the chamber flange. In each of the four corners, a small steel clip is bolted (the heads of the bolts are recessed in the wood). When this is done, the assembly is contact cemented to the face of the screen.

The phosphor for the screen is an activated zinc sulfide. It can be collected from the inner faces of old television picture tubes (not recommended, due to the danger of flying glass when the tube is broken open), or it can be bought from the Sargent-Welch Scientific Company. A one percent solution of collodion in acetone must be mixed, and a small quantity of phosphor powder is added. Using an inexpensive spray gun, the liquid is sprayed onto a flat sheet of clear celluloid, until a uniform layer of particles is seen. The acetone should evaporate almost immediately. Circles can be cut out of the plastic, taking care not to smudge the surface. One circle is lightly glued, using contact cement, to the center of the screen. Any extra circles can be saved as spares.

ELECTRICAL SYSTEM-

No problems should arise while building the electrical system if the schematic is followed carefully. Try to keep the

high voltage components about five centimeters apart, to reduce the chances of arcing. High voltage is a tricky thing, as I found out, and should be respected.

The transformer in the emission system must be hand made, as no transformer commercially available can withstand the high voltage flowing through the electron gun circuitry. If an ordinary transformer was used, the high voltage would destroy the insulation of both secondary and primary windings as it searched for ground. To eliminate this problem, I could have used a rechargable battery, but this would have been rather unsatisfactory. Instead, I removed the secondary winding from an old twenty five volt, eight ampere transformer, and wound as much steel core spark plug wire as possible in its place. Thus I had replaced the original secondary winding with a new one capable of withstanding close to twenty thousand volts. Since sparkplug wire is quite thick, the new winding is limited to about ten turns. If in doubt as to whether the new transformer will have enough power, hook a filament to it. If the filament becomes white hot, smokes, and burns out within about five seconds, the transformer is good. If the filament glows red or orange, try cramming on a few more turns of sparkplug wire. If this doesn'r work, a new transformer will have to be made.

Use sparkplug wire where high voltage is used. Do not let the wires cross one another, as even the best insulation can break down. Mount the entire electrical system in a heavy plywood box and extend the variable resistor shafts about eight centimeters with plastic rods. It is better to over space the components than to crowd them. When installing any of the resis-

tors, remember that the wattage can be increased but not decreased.

VACUUM SYSTEM-

Any mechanical diffusion combination that will attain 10^{-4} to 10^{-6} torr can be used to evacuate the T.E.M. Although some mechanical pumps have been advertised as being capable of reaching 10^{-4} torr, only a diffusion pump can reliably evacuate the microscope (while being backed by a mechanical pump, of course).

The choice of connections can have a very marked effect on the pumping speed at the vacuum chamber. Any connection placed between the pump and the chamber creates an impedance to the flow of gas. This is particularly true at low pressures, where the gas flow is substantially molecular in character. The gas flow is then dependant upon the kinetic activity of the molecules to bring it to the intake of the pump. The conductance of a tube is proportional to the cube of its diameter, and inversely proportional to its length. Therefore it is imperative that the connection be as large in diameter and as short in length as practical. For best results the diameter of the vacuum hose (I'm talking of inside diameter) should be at least as large as the diameter of the diffusion pump intake.

You will note that I avoided using cold traps or vacuum gauges. I felt that for a vacuum chamber as small as that of the Model 3, traps and gauges would be of questionable importance. The vacuum hose connecting the pump to the vacuum chamber should, for best results, have a minimum of bends. Clamp each and securely with an automotive type hose clamp.

OPERATION

Although the operating procedure of the Model 3 is more or less obvious, here is a brief description to be used as a guide.

Step 1- mount a specimen grid on the stage of the specimen grid holder. Insert the holder. Insert the electron gun and clamp it onto the chamber flange.

Step 2- turn on the mechanical pump, and when the pressure is no more than 1 torr, activate the diffusion pump heater and fan. Turn off any lights in the room.

Step 3- turn on the main power switch of the electrical system. Set the high voltage where desired. Increase the filament temperature until the viewing screen glows fairly bright. Now the shield bias can be adjusted to maintain a soft screen glow.

Step 4- increase the lens current until a sharp image can be seen on the screen. Adjust the electrical system controls in an attempt to clarify the image.

CAUTION

At no time during the operation of the microscope should any part of the microscope be touched. High voltage can leap surprising distances and it is possible to be electrocuted simply by getting too close to the connections (remember especially that the brass gun body is live). Even after shutdown, the filter capacitor for the acceleration system may retain a charge. Also do not handle the glass vacuum chamber carelessly during setup. One small chip or crack can result in an implosion when the air is removed by the evacuation system.

Shutdown - turn off the electrical system. Turn off the diffusion pump and wait until it is cool to the touch. The fan and mechanical pump can then be stopped and air admitted to the system.

As the Model 3 was designed to be a demonstration model for physics, high magnification was not a requirement. The Model 3 has a magnification of about 30X, and since little could be learned from a specimen at this power, I decided not to use specimens as such. Instead, the specimen grid itself is the specimen. If measurements are made of both the grid and image lines per centimeter, magnification can be calculated.

Here are some final notes that may be useful:

- do not heat the filament beyond a reasonable point. To do so will greatly shorten its life.
- always keep a few spare filaments, grids, phosphor screens, and O rings.
- keep the microscope away from metallic, magnetic, or electrical objects, which could disrupt the beam geometry.
- never allow the inside of the vacuum chamber to get dusty. For that matter, the exterior should also be kept clean.
- do not use vacuum grease indiscriminately, as it may create contamination problems.
- always check to make sure the vacuum hose is tightly connected to both chamber and pump.
- change the pump oil regularly to maintain high performance.
- keep all electrical connections clean.
- try small adjustments, such as extending or retracting the bias shield, to improve the beam geometry.
- replace the phosphor screen when light output decreases or screen blackens.
- admit air to the chamber slowly, as an accidental blast of air can damage the anode, aquadag, and phosphor screen.

- operate the microscope only in well ventilated areas. All mechanical vacuum pumps emit some oil vapour from the exhaust port, and research has shown oil vapour to be carcinogenic.
- do not overtighten the electron gun clamps on the chamber flange. Atmospheric pressure will seal the gun; overtightening may fracture the flange.
- tungsten evaporating from the filament will gradually deposit itself on and about the gun. At regular intervals it should be removed. This will prevent the gun from being shorted by the buildup.
- always plug the exhaust port when the pumps are disconnected.
- the weakest spot in the vacuum chamber is where the tungsten anode connection penetrates the glass wall. Care should be taken to prevent the connection from being banged, since even a small knock can fracture the seal.
- the specimen grid holder must be removed carefully so as not to loosen the press-fit anode.

CONCLUSION

A number of improvements were made on this T.E.M. after if was completed, thus necessitating this revised report. The construction information includes the changes I made.

I should point out that high speed electrons, on impact with glass, metal, etc. produce X-rays. Speedier electrons produce more intense radiation. Cancer, leukemia, premature aging, and unpredictable hereditary effects occur as a result of exposure to X-rays. My original electrical system contained 1B3GT high voltage rectifier tubes, which emitted a substantial amount of radiation. The present design incorporates ECG508 solid state rectifiers, which do not pose any hazard. The only problem is the microscope itself. At fifteen thousand volts, the electrons in the beam hit the anode, specimen, chamber walls, and screen at a velocity of 72,500 Kilometers per second. X-rays are produced. Although no more radiation than that produced by a television receiver is emitted, I personally feel that there does not exist a threshold level below which radiation damage does not occur. Therefore I suggest that the microscope should not be operated for longer periods than necessary. Perhaps someone else can devise a simple, effective means of shielding this T.E.M. with leaded plexiglas or another suitable material.

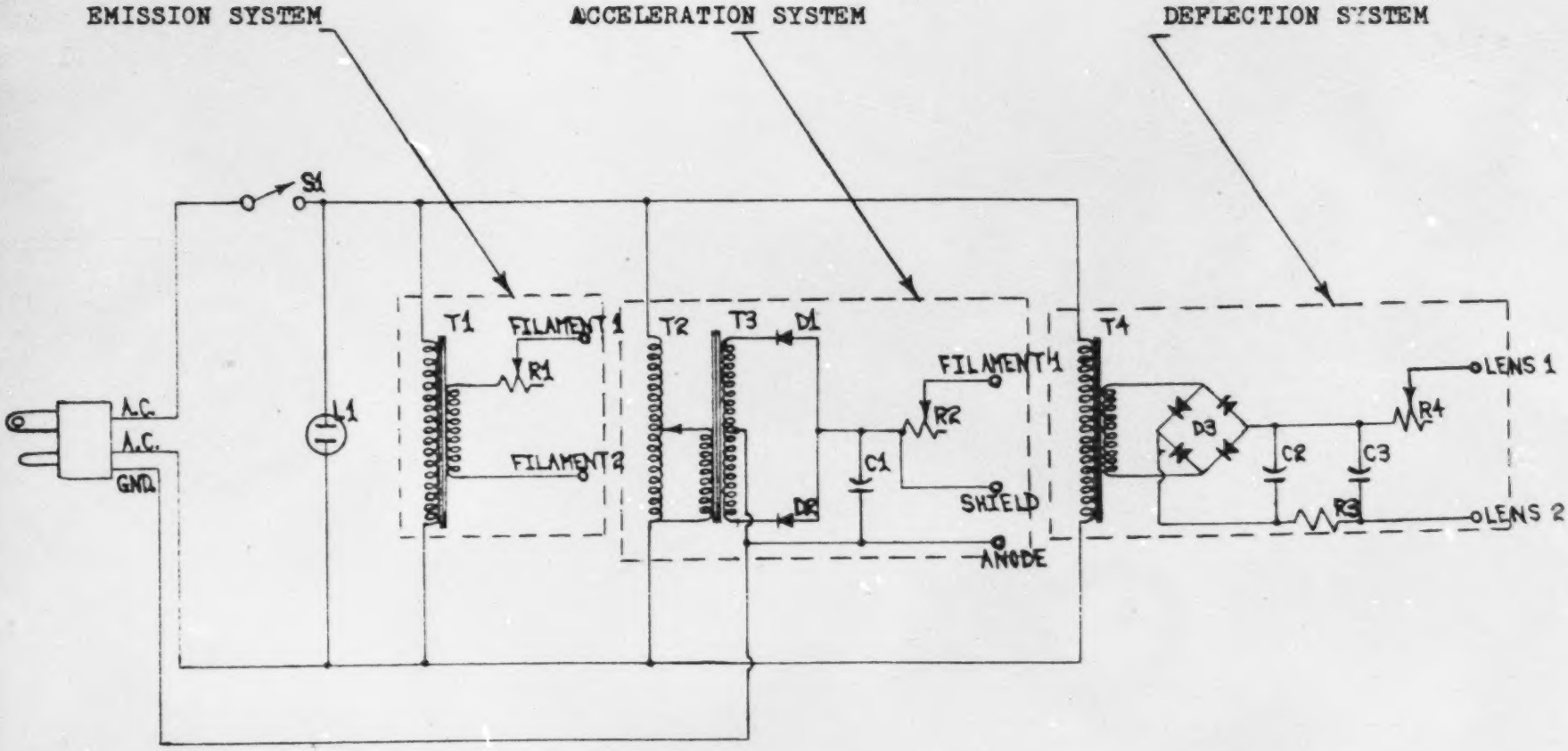
For any industrious readers who might be thinking of building their own T.E.M., I have these words : do not build a microscope identical to mine. Try moving the lens or adding more. Make a remotely adjustable specimen stage. Design a camera attachment and photograph the screen images. Build your own diffusion pump; it's not difficult and you'll certainly save money. If a part

cannot be found, invent! Why admit defeat when you can substitute with a design of your own? Improvisation is the key.

Not many years ago, amateurs in Canada and the rest of the world built computers, lasers, particle accelerators, and telescopes as a hobby. Bird watching, electronics experimentation, and model aviation and shipbuilding were very popular. Today educational, science related hobbies seem to be dying out, for reasons unknown to me. I hope that someone will read this paper and be encouraged to try a project of their own. Although frustrating at times, amateur science can be very rewarding.

CHART ENTITLED "TRANSMISSION ELECTRON MICROSCOPE, MODEL" REMOVED DUE TO OVERSIZE.

THE ELECTRICAL SYSTEM



COMPONENT LIST

C1- capacitor,500pF/20Kv. (Sprague 715 7322)
C2- capacitor,2200uF/35v. (R.S. 272 1020)
C3- capacitor,1000uF/35v. (R.S. 272 1019)
D1,D2- high voltage rectifier,20Kv. (ECG 508)
D3- bridge rectifier,50v/4A. (R.S. 1146)
L1- neon panel light.
R1- variable resistor,5ohms/20W.
R2- variable resistor,2Megohms/1W.
R3- fixed resistor,3ohms/10W. (R.S. 271 131)
R4- variable resistor,10ohms/25W.
S1- SPST switch,120v/10A.
T1- stepdown transformer,3v/5A. (home made; see CONSTRUCTION)
T2- variable transformer,0-120v. (Ohmite VT02 Ohmitran)
T3- stepup transformer,15Kv/30mA. (Acme 3015 center tapped)
T4- stepdown transformer,12.6v/3A. (R.S. 273 1511)

CHART ENTITLED "2 STAGE OIL DIFFUSION PUMP" HAS BEEN REMOVED DUE TO OVERSIZE.